

Galaxy Pairs in the Local Group

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ABSTRACT

Current models of galaxy formation predict that galaxy pairs of comparable magnitudes should become increasingly rare with decreasing luminosity. This seems at odds with the relatively high frequency of pairings among dwarf galaxies in the Local Group. We use literature data to show that $\sim 30\%$ of all satellites of the Milky Way and Andromeda galaxies brighter than $M_V = -8$ are found in likely physical pairs of comparable luminosity. Besides the previously recognised pairings of the Magellanic Clouds and of NGC 147/NGC 185, other candidate pairs include the Ursa Minor and Draco dwarf spheroidals, as well as the And I/And III satellites of M31. These pairs are much closer than expected by chance if the radial and angular distributions of satellites were uncorrelated; in addition, they have very similar line-of-sight velocities and luminosities that differ by less than three magnitudes. In contrast, the same criteria pair fewer than 4% of satellites in N-body/semi-analytic models that match the radial distribution and luminosity function of Local Group satellites. If confirmed in studies of larger samples, the high frequency of dwarf galaxy pairings may provide interesting clues to the formation of faint galaxies in the current cosmological paradigm.

Key words: galaxies: dwarf - galaxies: formation - galaxies: evolution - Local Group

1 INTRODUCTION

The shapes of the galaxy and dark halo mass functions differ substantially in the Λ CDM paradigm (see, e.g., Benson et al. 2003). This is usually interpreted to imply that the “efficiency” of galaxy formation, as measured by the ratio between the stellar mass of a galaxy (M_{gal}) and the virial¹ mass of its host halo (M_{200}), varies strongly with virial mass. In particular, M_{gal}/M_{200} should decrease steeply toward low halo masses in order to match the shallow faint end of the galaxy luminosity function (see, e.g., Moster et al. 2010; Behroozi et al. 2010; Guo et al. 2011).

On the scale of dwarf galaxies, which we define conventionally here as those with $M_{\text{gal}} < 10^{9.5} M_{\odot}$, simple abundance-matching models suggest a dependence nearly as steep as $M_{\text{gal}} \propto M_{200}^3$ in the dwarf galaxy regime (Guo et al. 2010). Such steep scaling would imply that dwarfs spanning several decades in stellar mass should nevertheless in-

habit halos of similar virial mass. In addition, extrapolating such models to the faintest galaxies known indicate that few, if any, galaxies more massive than a few million solar masses are expected to form in halos with virial mass below $10^{10} M_{\odot}$.

Recent work has highlighted potential disagreements between these model predictions and observations, including the lack of a characteristic velocity at the faint-end of blind HI surveys (Zwaan et al. 2010); and the low virial mass (substantially below $10^{10} M_{\odot}$) inferred from dynamical data for the dwarf spheroidal companions of the Milky Way (Boylan-Kolchin et al. 2012) and for nearby dwarf irregulars (Ferrero et al. 2012). It could be argued, however, that the evidence for substantial disagreement is unconvincing, given that the inferences are either indirect (in the case of the HI velocity function) or based on small and heterogeneous samples (in the case of the nearby dwarfs; see Wang et al. 2012; Vera-Ciro et al. 2012).

It is therefore important to consider further tests of the model predictions. We explore here how the steep $M_{\text{gal}}-M_{200}$ relation predicted for dwarfs affects the frequency of galaxy pairs of comparable luminosity. Such pairs, when close enough to inhabit the same dark matter halo (referred to hereafter as “physical pairs”), are expected to be rare at

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¹ We define all virial quantities as those corresponding to a sphere of mean density equal to 200 times the critical density for closure. Furthermore, we shall hereafter refer to the stellar mass of a galaxy as “galaxy mass”, for brevity.

all luminosities, but especially so in the scale of dwarfs. This is because the fainter companions in physical pairs trace the halo substructure, and subhalos are, by and large, far less massive than the main halo: the most massive subhalo typically has a mass only one hundredth that of the main system (see, e.g., Springel et al. 2008; Wang et al. 2012).

Pairs of comparable luminosity are therefore more likely to form in fairly massive halos, where galaxy formation efficiency decreases with increasing halo mass, partly compensating the mass difference between the main halo and its most massive subhalo. On dwarf galaxy scales the situation is reversed, and the precipitous decline in galaxy formation efficiency with decreasing halo mass should curb the formation of physical pairs of comparable luminosity. More generally speaking, isolated associations of dwarf galaxies should be rare. They are known to exist (e.g., Tully et al. 2006; Soares 2007), but their cosmological abundance and dependence on luminosity have not yet been adequately established (see Sales et al. 2012, for a recent attempt).

The Local Group offers an interesting environment to test these ideas. Advantages include the fact that, away from the “zone of avoidance” caused by Galactic dust, the census of Milky Way (MW) satellites brighter than $M_V \sim -8$ is complete (see, e.g., Whiting et al. 2007), and that accurate magnitudes, positions, distances, and line-of-sight velocities are known for all. Many fainter systems in the Local Group still remain undiscovered, as demonstrated by recent discoveries both by the Sloan Digital Sky Survey in the Milky Way (Koposov et al. 2008), and by the Pan-Andromeda Archaeological Survey around M31 (PAndAS; McConnachie et al. 2009). In the latter the census is likely complete within the PAndAS survey area down to a magnitude limit of $M_V \sim -6.5$, although some brighter dwarfs at larger radius likely have yet to be identified (as exemplified by the discoveries of Andromeda XXVIII and XXIX; Bell et al. 2011; Slater et al. 2011).

Further, we know that at least some of the satellites of the Milky Way and M31 are very likely physically associated and bound to each other. An obvious pairing is that of the Magellanic Clouds (see, e.g., Kallivayalil et al. 2006, and references therein). Around M31, there have been suggestions that NGC 147 and NGC 185 also form a bound pair (van den Bergh 1998). If these pairs are bound, their vicinity to their primary galaxy suggests that we are observing them just before they are separated by the tidal field of the main galaxy (Besla et al. 2007; Sales et al. 2011). This implies very recent accretion and indicates that their occurrence should not be uncommon amongst isolated systems.

Taken at face value, the existence of these two pairs of dwarfs seems at odds with the expected rarity of such associations. We use this as motivation to search, using literature data, for other dwarf galaxy pairs in the Local Group. We describe in Sec. 2 the observational dataset and the simulated satellite dataset we use for comparison. In Sec. 3 we introduce the pairing procedure we have adopted and compare the results with those obtained when the same procedure is applied to a hybrid N-body/semi-analytic model of satellite galaxy formation applied to N-body simulations from the Aquarius Project. We conclude with a brief summary in Sec. 4.

2 DATASETS

We use the recent compilation by McConnachie (2012) as the source of the positions, distances, line-of-sight velocities, and magnitudes of Local Group dwarfs that we use in our analysis. All velocities are heliocentric and corrected to the rest frame of the Galaxy. In order to prevent biases due to incompleteness, we consider only satellites brighter than $M_V = -8$ located within 300 kpc of the Milky Way or Andromeda (M31) galaxies. The sample consists of 29 dwarfs, 17 of which orbit around M31; the rest are satellites of the Milky Way.

For comparison, we have identified analogous samples of simulated satellites in the six $\sim 10^{12} M_\odot$ halos of the Aquarius Project (Springel et al. 2008) using the model of Starkenburg et al. (2012). This is a semi-analytic model grafted onto the level-2 Aquarius runs, which simulate each halo with several hundred million particles, thus ensuring a resolution high enough to track the formation of all halos and subhalos that might plausibly host the dwarf galaxies brighter than $M_V = -8$ we use in our analysis. The model satellites of each Aquarius halo have luminosity and radial distributions that are broadly consistent with the Milky Way and M31 and therefore provide a useful testbed of the significance of our results for Λ CDM dwarf galaxy formation models.

There are a total of 175 simulated satellites brighter than $M_V = -8$ within 300 kpc of the primary galaxies of all six Aquarius halos (on average 29 per halo). The model provides not only the full 3D position and velocity information for all of them, but also allows us to track their evolution. Our simulated sample does not include satellites whose dark matter halos have been fully disrupted by tides, since their fate is uncertain. We refer the interested reader to Starkenburg et al. (2012) for details on the semi-analytic model.

3 ANALYSIS AND RESULTS

It has long been noticed that the spatial distribution of Milky Way satellites is highly anisotropic (Lynden-Bell 1976), and is often described as a polar plane whose significance has been the matter of much recent debate (see, e.g., Kroupa et al. 2005; Zentner et al. 2005; Libeskind et al. 2005; Metz et al. 2007). Around M31, 14 out of 17 satellites in our sample are in the hemisphere nearer the Milky Way (McConnachie & Irwin 2006). Further, several have recently been shown to delineate a flattened structure that in total comprises at least half of all known M31 satellites (Ibata et al. 2013). These are unlikely configurations for a virialized population and hint strongly at recent accretion.

Our pairing procedure begins by identifying satellites whose nearest neighbour is unusually close when compared with the probability distribution of nearest-neighbour distances, d_{nn} , obtained by Monte Carlo sampling a random isotropic population of satellites with the same total number and radial distribution. We illustrate this in Fig. 1, where we show the d_{nn} distribution expected for two satellites of the Milky Way (Draco and Sagittarius), and two of M31 (And III and And IX).

The bottom left panel of Fig. 1 shows that the nearest satellite to Sagittarius (the LMC, 52 kpc away) is about

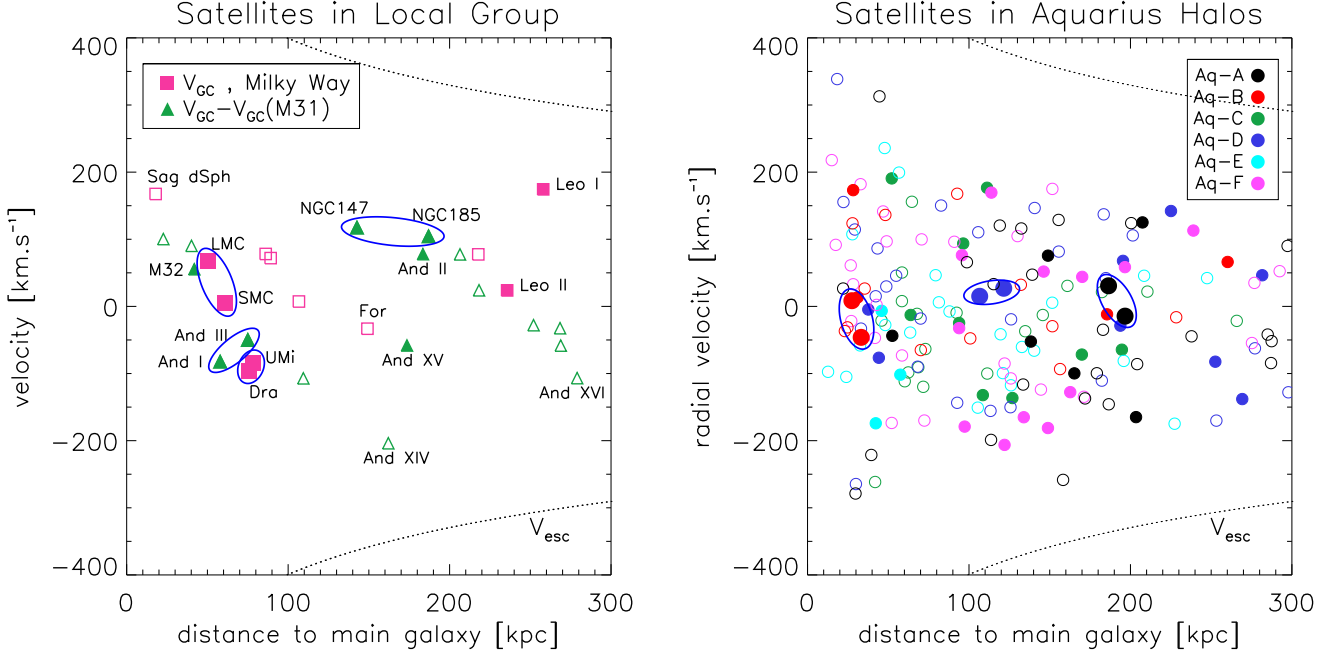


Figure 3. *Left panel:* Galactocentric velocity versus distance for Local Group satellites brighter than $M_V = -8$. Distances are measured from the center of each primary: MW satellites are shown as magenta squares; M31’s as green triangles. Velocities for the former are Galactocentric radial velocities; for the latter they refer to line-of-sight velocities relative to the systemic velocity of M31. Dotted curves indicate, for reference, the escape velocity from an NFW halo with virial velocity $V_{200} = 250$ km/s and concentration $c = 10$ (Navarro et al. 1997). Filled symbols highlight satellites with a nearest neighbour much closer than expected by chance ($P < 0.2$, see Fig. 2). Pairs satisfying additional proximity criteria in velocity ($\Delta V < 75$ km/s) and magnitude ($\Delta M_V < 3$) are joined together by ellipses to indicate that they are likely physical pairs. These constitute 28% of the total and include (i) the Magellanic Clouds; (ii) NGC 147 and NGC 185; (iii) Ursa Minor and Draco; and (iv) And I and And III. *Right panel:* Same as left panel, but for the semi-analytic satellite population of the six Aquarius halos. Different colors correspond to different halos. Note that the same criteria that pair 28% of Local Group satellites link only six satellites in the Aquarius simulations, or just 3% of the total.

this is also consistent with the idea that most dwarfs should inhabit halos of similar mass (see Sec. 1) (see Sales et al. 2012, for a more thorough discussion). Finally, since we are mainly interested in pairs of comparable luminosities we retain as likely pairs only those where their magnitudes differ by $\Delta M_V < 3$.

Four pairs remain after applying these constraints, as shown in Fig. 3. Around the Milky Way, aside from the Magellanic Clouds, the Ursa Minor and Draco pair is singled out: they are 23 kpc apart, and their velocities differ by only 12 km/s. Further, they have both approximately the same luminosity, which makes them especially singular. The procedure also joins together two pairs of satellites around M31: NGC 147 and NGC 185, as well as And I and And III. The latter are separated by 33 kpc; differ in velocity by just 32 km/s; and in magnitude by 1.7.

This analysis suggests that nearly 30% of Local Group satellites are in likely pairs (8 out of 29). Of the four pairs, two are almost indisputably associated (the Magellanic Clouds and NGC 147/NGC 185; see, however, Geha et al. 2010 for an alternate view of the latter) but the other two might in principle result from chance close encounters between unrelated satellites where projection effects reduce the line-of-sight velocity difference. In order to quantify these effects we have applied the same pairing procedure to the satellite populations of the six Aquarius halos, as identified by the semi-analytic model of Starkenburg et al. (2012).

The blue dotted histogram in Fig. 2 shows that the P distribution for Aquarius satellites differs little from that expected from an isotropic distribution. Only 27% of the 175 satellites have $P < 0.2$; of those only 3 pairs (i.e., fewer than 4%) pass as well the velocity and magnitude criteria. The three Aquarius pairs (out of six halos) singled out by the analysis are shown in the right-hand panel of Fig. 3. Tracking their orbits back in time reveals that none of them are actually physically related but that they result simply from chance, transient associations in position and velocity space. Note that this does not imply that *all* satellites have been accreted in isolation. As discussed by Wang et al. (2012), a few of the bright satellites in Aquarius were accreted in groups, but the accretion happened early and the groups have long been disrupted by the tidal field of the main halo. This confirms the model expectation that physical associations amongst *satellites* should be extremely rare. The relatively high frequency of satellite pairings in the Local Group indicates that the radial and angular distributions of satellites are correlated, a fact that is not easily accounted for by current dwarf galaxy formation models in the Λ CDM paradigm.

4 SUMMARY AND CONCLUSIONS

We have studied possible pairings amongst the satellites of the Milky Way and of M31. Our procedure, which identifies unusually close associations in position and velocity space, suggests that 8 out of the 29 satellites brighter than $M_V = -8$ (i.e., nearly $\sim 30\%$) form 4 likely pairs of comparable luminosity ($\Delta M_V < 3$). These include the Magellanic Clouds; Ursa Minor and Draco; NGC 147 and NGC 185; as well as And I and And III.

The same pairing procedure applied to a semi-analytic model of the satellite population in the six halos of the Aquarius Project yields a likely pair fraction of fewer than 4%, even though the model satellites have luminosity and radial distributions that match closely that of the Local Group spirals. As expected, none of the Aquarius pairs correspond to true binary systems; rather, they result from transient associations between otherwise unrelated satellites. The high pair frequency of the Local Group is unlikely to be just a statistical fluke: the likely pair fraction of Aquarius satellites never exceeds 12% in thousands of random trials where their magnitudes, angular directions and velocities are reshuffled.

We interpret these results as indicative of significant clustering in the dwarf galaxy population of the Local Group. Although our analysis only considers satellites brighter than $M_V = -8$ due to incompleteness concerns and in order to allow comparison with simulations, there have also been suggestions that some of the fainter Galactic satellites are found in associations. In particular, Belokurov et al. (2008) show that Leo IV and Leo V are close to each other spatially and differ little in their line-of-sight velocities. Further, the association of galaxies closest to the Local Group, sometimes referred to as the loose NGC 3109 group (van den Bergh 1999), consists of four dwarf galaxies (NGC3109, Antlia, Sextans A and B), two of which appear to be interacting (NGC3019 and Antlia; see Barnes & de Blok 2001). These associations are expected to be rare according to current Λ CDM galaxy formation models, and may signal the presence of a mechanism that boosts the likelihood of forming dwarf galaxies near other dwarfs, favouring some environments over others. No such effect is present in current models of dwarf galaxy formation, which rely largely on the mass accretion history of individual halos to set the properties of a dwarf.

Candidate mechanisms that may bias the regions where dwarf galaxies form in a way that enhances their clustering include patchy reionization (see, e.g., Lunnan et al. 2012); large-scale feedback effects on the surroundings of massive galaxies (Alvarez et al. 2009; Busha et al. 2010; Font et al. 2011); and the interaction of dwarf galaxies with the cosmic web (Benítez-Llambay et al. 2012). However, the effects of these models on dwarf galaxies have yet to be developed fully and as a consequence the importance of such effects on the dwarf galaxy population at large is still unknown.

It is therefore important to firm up these findings (i) by extending the analysis to fainter satellites, which should be possible once photometric surveys of the northern and southern sky extend the complete catalog of Milky Way satellites to fainter magnitudes; (ii) by verifying, through accurate proper motion studies, that the associations in position and line-of-sight velocities remain once the full 6D phase space information is considered; (iii) by searching

for relic evidence of past interactions between likely pairs (such as the Magellanic Stream for the LMC/SMC (see, e.g., Mathewson et al. 1974; Putman et al. 1998); and, finally, (iv) by extending this kind of analysis to a volume-limited survey of dwarf galaxy associations in the local universe (see, e.g., Karachentsev & Makarov 2008). If confirmed, the enhanced clustering of dwarfs may offer important clues to the formation of faint galaxies that have yet to be identified and fully incorporated into galaxy formation models.

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